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RESEARCH MEMORANDUM

EVALUATION OF THE USE OF ELECTRICAL RESISTANCE FOR DETECTING OVERTEMPERATURED S-816 TURBINE BLADES

By Leonard Robins

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NATIONAL ADVISORY COMMITTEE
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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUM

EVALUATION OF THE USE OF ELECTRICAL RESISTANCE FOR DETECTING OVERTEMPERATURED S-816 TURBINE BLADES

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SUMMARY

The feasibility of using an electrical resistance test for detecting overtemperatured S-816 turbine blades was studied. The variation in the electrical resistivity and hardness of new turbine blades and heat-treated bar stock was determined. The variation in resistance due to the variation in geometry was evaluated from measurements of the cross-sectional areas of blades.

The resistivity changes for S-816 thermally treated at temperatures higher than the normal turbine blade operating temperature were dependent on time and temperature and were less than the scatter in resistivity for specimens cut from new blades chosen at random. Hardness and resistivity values generally were not related. Resistance measurements made on a blade airfoil may be influenced by the variation in cross-sectional area due to dimensional tolerances to an extent that exceeds the effects of fabrication variables and overtemperature operation. It was concluded that a nondestructive resistance test to detect the overtemperature of S-816 turbine blades may be possible only if resistance measurements are made before and after engine operation or suspected overtemperature. Under conditions where the operating times and resistance records are not kept for individual S-816 blades, it is believed virtually impossible to detect overtemperature by resistance measurements.

INTRODUCTION

The normal operating temperature of S-816 turbine blades in jet engines is about 1500° F. Under certain conditions the blades may be exposed to temperatures above 1500° F, and they are then said to have been overtemperatured. The exposure may vary from a few seconds for severe overtemperature during transient engine operation to many hours for moderate or slight overtemperature during engine or control malfunction. Since the overtemperature can occur at any engine speed, the stress in the blade during overtemperature may be either at or lower than the stress at maximum rated engine speed. In cases where the engine is overspeeded the overtemperature can occur at a stress which is above that at maximum rated power.

A blade that has been overtemperatured may undergo structural changes which can affect the strength of the alloy. This is indicated by reference 1 which states that when specimens of S-816, which previously had been given the standard heat treatment of 1 hour at 2150° F followed by 16 hours at 1400° F, were heated (overtemperatured) for several hours in the range of 1600° to 2000° F, the 1500° stress-rupture life was decreased. On the other hand, the same reference indicated that similar heating at 2150° F increased the 1500° F life.

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A nondestructive technique capable of determining if a blade has been overtemperatured would be useful as a guide for blade replacement and avoiding flight accidents.

Replacement of blades suspected of having been overtemperatured is, at present, based largely on a visual inspection for obvious damage. More rigorous inspections are made or the blades are replaced when the pilot reports that the engine has exceeded certain maximum temperature limits. In many instances, however, the pilot is unaware of the overtemperature condition. More rigorous inspections are also made when other engine components indicate overtemperature has occurred.

The overtemperature problem is discussed in greater detail in references 2 and 3. These references also emphasize the need for some satisfactory means of detecting overtemperature in blades in order to reduce the possibilities of engine failure by defective blades and give added protection to crews and aircraft. Reference 4 reports that the use of physical measurements (including electrical resistance) for the detection of minute internal cracks in forged turbine components has not been successful, because these defects give signals smaller than are obtained with the normal variation in surface condition and dimensional tolerances.

The purpose of this investigation is to explore further the possibility of using electrical resistance as the basis for a test to determine if turbine blades have been overtemperatured.

In evaluating the feasibility of detecting overtemperature in turbine blades by resistance measurements it must be shown first that the overtemperature produces a measurable change in resistance. This can best be done by studies of homogeneous bar stock. Secondly, it must be shown that this change is not obscured or overshadowed by the variability of the blade material or geometry. Presuming that measurable changes in resistivity are not overshadowed by the variability of the blades, several approaches could be used to determine if a given blade had been overtemperatured. Three approaches that appear reasonable are:

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(1) Determining if the resistance of a specific location on turbine blades selected at random from a wheel exceeds a value which has been predetermined to be indicative of an overtemperatured condition.

(2) Determining the resistance of the blade along the span. Since the overtemperature is generally severely localized in the blade, it would appear reasonable to expect a discontinuity in this region in the resistance against blade span curve for overtemperatured blades.

(3) Recording the resistance of several selected new blades before they were operated, identifying these blades, and comparing with periodic measurements of the resistance of the same blades.

Of these methods, (1) is preferred because it does not require recording the histories of the blades and needs only a single measurement on each blade. It does, however, have the disadvantage (as will be discussed in greater detail later in this report) of requiring accurate positioning of the probing device used for making the measurements. Method (2) also has the attractive feature of not requiring the blade history; it does, however, require a series of measurements.

This report consists of a series of brief studies in which the factors which affect the use of resistance were studied independently. The cobalt-base alloy S-816 was used in this study. The factors studied were: (1) the resistivity of randomly selected new blades, (2) the resistivity of specimens which had been heat-treated to simulate and exaggerate various degrees of overtemperature, and (3) the variation in the cross-sectional area of the airfoil possible within the dimensional tolerances.

MATERIALS, APPARATUS, AND PROCEDURE

Composition and Structure of S-816

The nominal chemical composition of S-816, an age-hardenable cobalt-base alloy, is:

Element	Co	Cr	Ni	Mo	W	Cb + Ta	C	Fe	Mn
Weight, percent	40 (Minimum)	19-21	19-21	3.5-4.5	3.5-4.5	3.5-4.5	0.32-0.42	5 (Maximum)	1

The standard heat treatment for forged S-816 turbine blades is, in the order of treatment:

(1) Solution treatment: 2150° F, 1 hour, water-quenched

(2) Aging treatment: 1400° F, 16 hours, air-cooled.

A representative resultant microstructure (fig. 1(a)) consists of hard residual (Cb, Ta) C-type carbides and other carbides in the grains and at the grain boundaries of a ductile solid-solution matrix. The main feature distinguishing the microstructure of a severely overtemperatured sample is the dissolution of the grain boundary precipitate (figs. 1(b) and (c)). Lesser degrees of overtemperature would merely increase and agglomerate the precipitate.

Description of Specimens

Resistivity specimens from bar stock. - To provide specimens with a high degree of uniformity, hot-worked S-816 bar stock was used. Detailed information about specimen sizes will be found in the section Overtemperature Heat Treatments.

Resistivity specimens from turbine blades. - In order to determine the scatter in the resistivity of forged S-816 turbine blades, 15 J47-GE-25 blades were chosen at random from several hundred new blades. The blades chosen represented six different vendors and indicated the range of resistivity resulting from the normal thermal and mechanical fabrication variables which occur during manufacture. Two specimens, about $1\frac{1}{2}$ by $\frac{3}{16}$ by $\frac{1}{8}$ inch, were machined from the airfoil near the leading edge of each of the blades as shown in figure 2.

Turbine blades for area and resistance studies. - To indicate the scatter in cross-sectional area that exists in production blades, the areas of three new blades, from different vendors, were measured.

A used blade was employed to determine the reproducibility of resistance measurements of blade airfoils. Surface scale was removed from this blade by light vapor blasting prior to making the resistance measurements.

Overtemperature Heat Treatments

Temperature gradient studies. - In order to determine whether resistance measurements can detect an overtemperature condition and to determine the magnitude of resistivity discontinuities produced artificially by heat treatment in bar stock, four specimens, each 5.0 by 0.300 by 0.300 inch, were made from a piece of bar stock $\frac{25}{32}$ inch in diameter and 10 inches in length. After receiving the standard heat treatment, the specimens were heated in air by an induction coil around their midsections. The highest temperature was measured by a Chromel-Alumel thermocouple spot-welded to the midsection. A temperature gradient extended from the maximum temperature at the center to an estimated 300° F at the ends of the specimen. The midsection of each specimen was heated for 15 minutes at 1800°, 2150°, or 2250° F. After air-cooling the specimens, the thermocouples were removed and the surfaces were polished with fine emery cloth to remove the scale which formed at the midsections.

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Constant temperature studies. - In order to determine the magnitudes of the resistivity changes due to time and temperature, specimens were made from another lot of bar stock. Bar stock ($1\frac{1}{4}$ in. square) from one heat was hot-rolled and sawed into slugs $\frac{7}{8}$ inch square and $2\frac{5}{8}$ inches long. All slugs were given the standard heat treatment simultaneously. The slugs were machined into specimens $2\frac{5}{8}$ by 0.20 by 0.20 inch, heat-treated in an argon atmosphere at 1600°, 1800°, 2000°, or 2200° F for periods of 2, 20, and 75 hours, and air-cooled, one specimen being used for each condition. Final machining to clean the surfaces reduced the cross-sections of the square specimens to 0.168 inch on a side.

Tests and Evaluations

Resistance testing. - The equipment and procedure employed for resistance measurements were as follows:

Equipment: The schematic circuit diagram for measuring the resistance of the specimens is shown in figure 3. A Kelvin bridge was used to measure the resistance between the points where the potential probes contact the test specimen. The potential probe span was 0.75 inch. The Kelvin bridge eliminates the effect of contact resistances, is suitable for measuring resistances from 0.00001 to 10.1 ohms, and gives estimated readings down to 0.0000001 ohm. An external spot-light galvanometer and 6-volt battery were used. The current drawn from the battery was kept at about 8 amperes by means of a variable resistor. Reference 5 gives detailed information about the bridge employed.

The apparatus for measuring either blades or resistivity specimens is shown in figure 4. The resistance measurements of a blade were made on the airfoil since this is where overtemperature is most severe and where blade failure normally occurs during jet engine operation. Current contact to the blade is made through the two mercury wells. The tip of the airfoil protrudes through an opening in a sponge-rubber seal at the bottom of the upper mercury well; this seal also holds the blade. The dovetailed root section of the blade is suspended in the lower mercury well. A micromanipulator was employed to locate the potential probes at the desired points on the airfoil.

Procedure: The resistance of the portion of the test specimens between the potential probes was measured by sending a current through the circuit and varying the resistance in the Kelvin bridge until it equalled the unknown resistance. At this point, since the current through the bridge resistors is the same as that through the test specimen, the potential drop across the bridge resistance balances the potential drop along the part of the specimen between the potential probes, so that no current passes through the galvanometer. The unknown resistance is then read directly from the dial settings of the bridge when the galvanometer pointer gives no deflection. 4097

Resistance measurements were made at four fixed locations along the span at the midchord of an airfoil. These measurements were repeated as several traverses were made. In some tests the blade was removed from the holding fixture between traverses.

The resistivity data in the temperature gradient study were obtained by repeatedly traversing the specimen and, in several cases, traversing after the specimen was removed and repositioned. In the course of obtaining the data in the constant temperature and blade resistivity studies, the specimen was repositioned several times.

The electrical resistivity ρ was calculated from the equation $\rho = R\frac{A}{l}$ where R is the electrical resistance in ohms, A is the cross-sectional area of the specimen in square centimeters, and l is the distance in centimeters across which the potential drop is measured. This equation is valid for current flow parallel for a length l over a constant area A in a material of constant resistivity ρ.

For the specimens which had been exposed to temperature gradients and for the used turbine blade, relatively large resistance variations occurred as the potential probes traversed the length of the specimen. When plotting the data in these two cases, a measured resistance was considered to be located at the midpoint of the probe span.

Hardness testing. - In order to compare the resistance data with data from a commonly employed quality control test for S-816, hardness was measured on a standard Rockwell tester.

Determining cross-sectional area of blades. - In order to evaluate the effect of variations in the cross-sectional area of the airfoil on the resistance of a blade, the area was determined at several stations on the blade airfoil from specifications and measurements made on blades.

The nominal area was determined from the specifications for the J47-GE-25 turbine blade by laying out the profile at the desired location and measuring the area with a planimeter. In a similar manner, the largest area permitted at the same locations was determined by superimposing the positive tolerances of the specifications. The negative tolerances were much smaller than the positive tolerances and thus caused only a small decrease in nominal area. It was therefore assumed that, to a first approximation, the difference between the nominal area and the largest area represents the maximum variation in area of an airfoil.

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A visograph was employed to record the profiles of the three new blades from different vendors. The area of the plots was measured with a planimeter.

RESULTS AND DISCUSSION

Effect of Overtemperature Heat Treatments on Homogeneous Bar Stock

Only severe overtemperature can result in a sufficient change in the resistivity of bar stock to permit detection. The resistivity changes resulting from mild overtemperatures fall within the scatter band of the untreated material. Figure 5 shows the resistivity changes resulting from imposing various temperature gradients on the specimens from bar stock for 15 minutes. The maximum temperature region is at the center. Outside of the hot zone, almost all resistivity measurements made on the heated specimens fall within the range of values for an untreated specimen. Resistivity measurements made in the hot zone of the specimen heated to 1800° F also were within the range of those for the untreated specimen. However, the hot zones for the 2150° and 2250° F specimens could be clearly detected by the resistivity peaks at this region (see fig. 5(a)). The hardness was measured on only the 2250° F specimen. The hardness change for this specimen also enabled the identification of the hot zone as shown in figure 5(b).

Time at constant temperature was also found to influence the resistivity. The resistivity and hardness of the uniformly heat-treated specimens from bar stock are listed in table I and plotted in figure 6. The largest resistivity decrease shown in figure 6(a) was 1.50 percent below the resistivity of the standard (untreated) specimen. This change took place after 2 hours at 1800° F. The largest increase, 1.64 percent, occurred at 2200° F, also after 2 hours. The total percentage variation was thus 3.14 percent. After the initial resistivity changes occurred, all resistivity values tended to converge toward the value for the untreated specimen. The 1600°, 1800°, and 2000° F values were almost identical after 75 hours. For some overtemperatures between 2000° and 2200° F the resistivity, after certain times, must equal that of the untreated specimen since all values for 2000° F are below the untreated value and those for 2200° F, above. Figure 6(b) shows that the only appreciable hardness changes took place at 2200° F where the hardness decreased with time at temperature.

In considering the above data it should be recalled that overtemperatures can occur when stresses are either high or low. The effect of overtemperature on resistivity when material is stressed is unknown and would require a separate study.

Effect of Blade Variability

Variations in properties of new blades. - It has been shown that severe overtemperatures can be detected in homogeneous bar stock. Whether 4097
or not the resistance scatter band due to fabrication variables overlaps that for overtemperature operation is an important consideration in evaluating the electrical resistance test to detect blades that have been at overtemperature. The resistivity and hardness of specimens machined from new blades are listed in table II and plotted in figure 7. The dotted lines represent the maximum scatter of this data. The range of resistivity and hardness obtained on specimens by heat treatment alone and taken from figure 6 is also shown. A comparison of these bands indicates that (except for the hardness values at 2200° F) the resistivity and hardness values for the heat-treated bar-stock specimens fall within the bands of scatter for the specimens cut from blades.

The maximum variation for specimens from blades (97.826 microhm-cm) increased 4.48 and decreased 2.77 percent from the average resistivity value, giving a total variation of 7.25 percent. It is evident that the effect of fabrication variables on resistivity exceeded that produced by heat treatment. This may not be true when all blades are from the same vendor. Figure 7(a) indicates that the resistivity scatter band for some vendors is, on the basis of a few blades per vendor, smaller than the variation due to heat treatment.

No relation between hardness, resistivity, and location of specimens from blades was detected (table II). The scatter in resistivity and hardness of specimens from new blades reflects the variations in thermal and mechanical histories between the blades. The resistivity and hardness of the blades are affected by the differences introduced during fabrication; differences, for example, in composition (due to changes in the charge for melting or melting procedure), residual stresses (due to variations in forging and finishing operations), and size and distribution of the precipitates (due, for example, to differences in heat treatment).

Variations in blade geometry. - The allowable variations in cross-sectional area for various locations on the airfoil are listed in table III. These data, which include measurements made on three new blades, are plotted in figure 8.

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Since electrical resistance is inversely proportional to cross-sectional area, a small increase in area will cause a similar decrease in resistance. The dashed curves in figure 8 are the limits for the variation in the measured cross-sectional area of three new blades. The solid curves represent the nominal area (approximately equal to the minimum area) and maximum area according to the dimensional tolerances given in the blade specifications. The specifications permit an increase in the areas at the various stations from 8 percent of the nominal area (near the base) to $14\frac{1}{2}$ percent (near the tip). The measured blades (dashed lines) showed a variation from $1\frac{1}{2}$ percent (near the base) to $10\frac{1}{2}$ percent (near the tip). Thus, the percentage variation in area increases from the root to the tip of the blade. The variation in airfoil resistance due to these area variations can exceed the resistance variations for the previously noted effects of overtemperature heat treatments (maximum resistance variation, 3 percent) and fabrication variables (maximum resistance variation, 7 percent).

An indication of the reproducibility of the technique used to measure the resistance of the airfoil of a turbine blade is shown in table IV. The average value of the resistance determinations made for five traverses of the airfoil is listed for each setting of the probes. Also listed is a duplicate set of values obtained after removal and reinsertion of the blade in the holding fixture. The reproducibility of probe positioning is indicated by the mean deviation of the five separate values from the average value. The over-all reproducibility that would be encountered with repeated measurements (at various time intervals) of a blade can be estimated from the discrepancy between values for the duplicate blade measurement. The large differences in resistance between the sections of the airfoil, shown in table IV, require that great care be taken in relocating the potential probes when reproducing resistance measurements on a blade airfoil.

It is believed that the percentage mean deviation and percentage difference in resistance values for a blade can be reduced further by suitable refinement of the blade holding and probe positioning devices. While the accuracy with which a resistance measurement can be made on the airfoil is not as high as that made on the regular-shaped specimen, the technique employed to measure the resistance of the blade appears to yield reproducible values.

CONCLUDING REMARKS

This study has shown that for S-816 the resistivity changes produced by mild overtemperature heat treatments (up to about 2000° F) fall within the scatter of the resistivities of the homogeneous alloy. The literature indicates that these mild overtemperatures are detrimental to blade life.

In the case of severe overtemperature measurable resistivity changes occur. In the case of turbine blades where the prior history is not known, however, even the effects of very severe overtemperature probably cannot be found by resistance measurements because of the structural and dimensional variabilities of the blades.

Another method suggested for using resistance to detect overtemperature in a turbine blade is examining a plot of the resistance along the blade span. It was expected that this plot would have a discontinuity where the overtemperature occurred. The data indicate that for such a discontinuity to exist, the overtemperature must be unusually severe; thus, this method would not be particularly useful. Furthermore, it is probable that the curve of resistance along the airfoil span is not smooth because of variations in the blade chemistry and metallurgical structure.

Finally, there is the possibility of determining if turbine blades have been overtemperatured by logging the resistances of several selected new blades before they are operated, identifying these blades, and periodically remeasuring the same blades. It appears that, if sufficient care is used in positioning the probes for making the resistance measurements, this method could be used, but only to indicate that the blades of a turbine wheel had been exposed to very severe overtemperature.

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SUMMARY OF RESULTS

An exploratory study was made to determine the usefulness of an electrical resistance test for detecting overtemperatured S-816 turbine blades not subjected to stress during the overtemperature. The following results were obtained:

1. A detectable resistivity change occurred in S-816 bar stock after 15 minutes of overtemperature at 2150° or 2250° F, but there was no significant change after overtemperature at 1800° F.

2. Bar stock overtemperatured at 2200° F for 2 to 75 hours had higher resistivities than either bar stock overtemperatured for equivalent times at 2000° F or below or bar stock given only the standard heat treatment.

3. Bar stock overtemperatured at 1600° to 2000° F for 2 to 75 hours had resistivities which were approximately equal and only slightly different from the value for bar stock given only the standard heat treatment.

4. For bar stock overtemperatured between 2000° and 2200° F there must be combinations of time and temperature that will result in resistivities identical to those for bar stock which has not been at overtemperature.

5. The scatter in resistivity for new blades was so great that it exceeded the resistivity changes produced by heat-treating the bar stock.

6. There was no simple relation between resistivity, hardness, and location at which these measurements were made on new turbine blades.

7. The percentage variation in area permitted by dimensional tolerances for turbine blades can cause greater changes in resistivity than the effects of overtemperature.

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8. The area of a blade airfoil increased rapidly in traversing from the blade tip to the base. Thus, great care had to be taken in relocating the potential probes to reproduce resistance measurements.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, January 30, 1957

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TABLE I. - PROPERTIES OF HEAT-TREATED S-816

Heat treatment (a)		Electrical resistivity, microhm-cm	Hardness[b], Rockwell-	
Temperature, °F	Time, hr		C-	A-
Untreated (given only standard heat treatment for S-816)	--	97.33	28	64.5
1600	2	97.73	28	64.5
	20	96.16	29	65.0
	75	96.81	27	64.0
1800	2	95.87	28	64.5
	20	96.71	27	64.0
	75	96.81	26	63.5
2000	2	96.24	26	63.5
	20	96.79	24	62.5
	75	96.92	24	62.5
2200	2	98.93	21	61.0
	20	97.95	--	59.0
	75	97.76	--	57.5

[a]All specimens had previously been given the standard heat treatment for S-816.

[b]The Rockwell C- scale was used for all hardness measurements above Rockwell C-20 (Rockwell A-60.5). The Rockwell A- scale was used below Rockwell C-20. All other Rockwell A- hardness values in the table are converted from the Rockwell C- measurement.

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TABLE II. - PROPERTIES OF SPECIMENS MACHINED

FROM NEW S-816 TURBINE BLADES

Specimen designation			Electrical resistivity, microhm-cm	Hardness, Rockwell C-
Blade number	Location (a)	Vendor		
1	U	A	98.78	28
1	L	A	102.2	24
2	U	A	98.30	27
2	L	A	98.29	27
3	U	A	96.41	30
3	L	A	96.31	32
4	U	A	97.11	28
4	L	A	96.78	26
5	U	B	97.09	28
5	L	B	97.85	26
6	U	B	98.16	29
6	L	B	95.12	33
7	U	B	100.6	30
7	L	B	96.62	26
8	U	C	98.06	28
8	L	C	96.85	27
9	U	C	96.73	28
9	L	C	97.30	31
10	U	C	97.88	30
10	L	C	99.13	31
11	U	D	98.92	25
11	L	D	98.40	26
12	U	D	98.90	26
12	L	D	98.93	23
13	U	E	97.95	26
13	L	E	98.68	28
14	U	E	97.96	26
14	L	E	97.88	25
15	U	F	95.83	26
15	L	F	95.76	26

[a]U, from upper leading edge; L, from lower leading edge.

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TABLE III. - CROSS-SECTIONAL AREA OF FORGED S-816 TURBINE BLADES

Station	Height of station above base, in.	Area, sq in.				
		Nominal area (approx. minimum area allowed by specifications)	Maximum area allowed by specifications	New blade area		
				Blade 1	Blade 2	Blade 3
A	0.358			0.5388	0.5394	0.5499
B	.958	0.4331	0.4671	.4461	.4471	.4527
C	1.883	.3318	.3656	.3394	.3416	.3563
D	2.808	.2415	.2763	.2524	.2464	.2633
E	3.508			.1911	.1726	.1863

TABLE IV. - ELECTRICAL RESISTANCE OF AIRFOIL

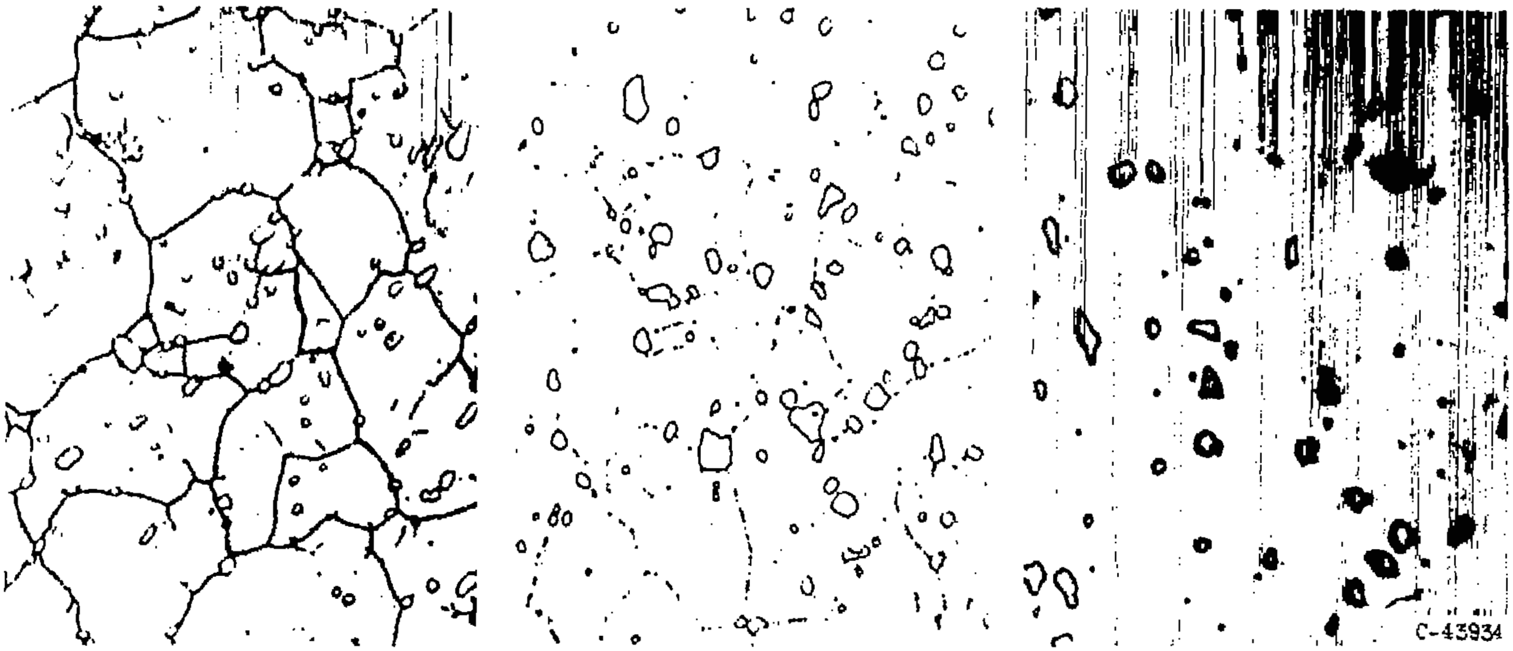
OF S-816 TURBINE BLADE

Distance above base of the blade, in.	Resistance, microhms[a]				Percentage difference between measurements
	Measurement one		Measurement two[b]		
	Average (c)	Mean deviation, percent	Average (c)	Mean deviation, percent	
2.50	101.1	±0.4	100.6	±0.4	0.5
2.25	96.2	±.4	97.5	±1.2	1.3
2.00	89.2	±.7	88.5	±.6	.8
1.25	70.1	±1.1	71.8	±1.5	2.4

[a]For a potential probe span of 0.75 in.

[b]Blade removed and replaced into holder.

[c]Average for five separate resistance traverses.



(a) Standard heat treatment: 1 hour at 2150° F, water-quenched; 16 hours at 1400° F, air-cooled.

(b) Overtemperatured 15 minutes at 2000° F following standard heat treatment.

(c) Overtemperatured 15 minutes at 2150° F following standard heat treatment.

Figure 1. - Effect of overtemperature on microstructure of S-816. X1000.

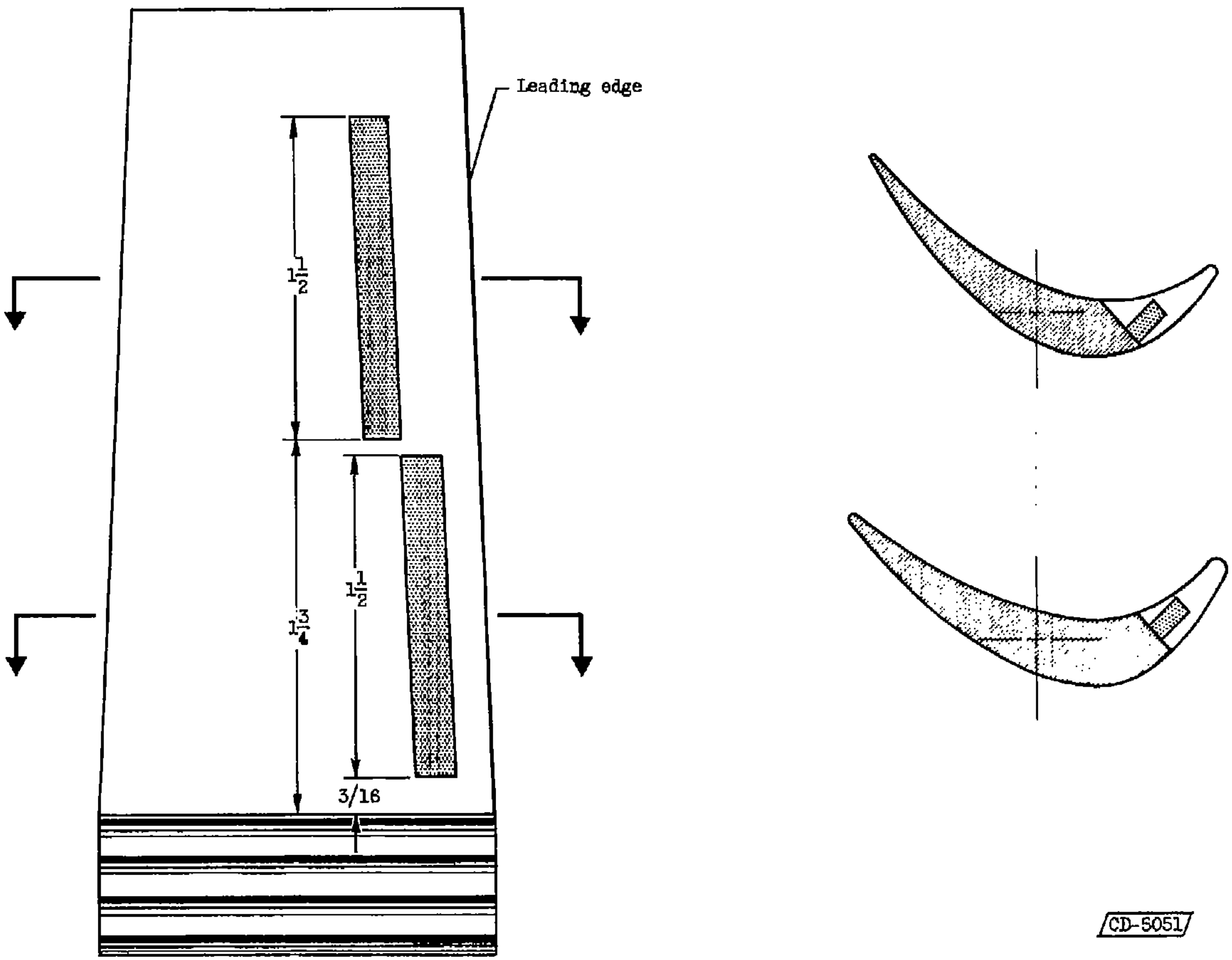
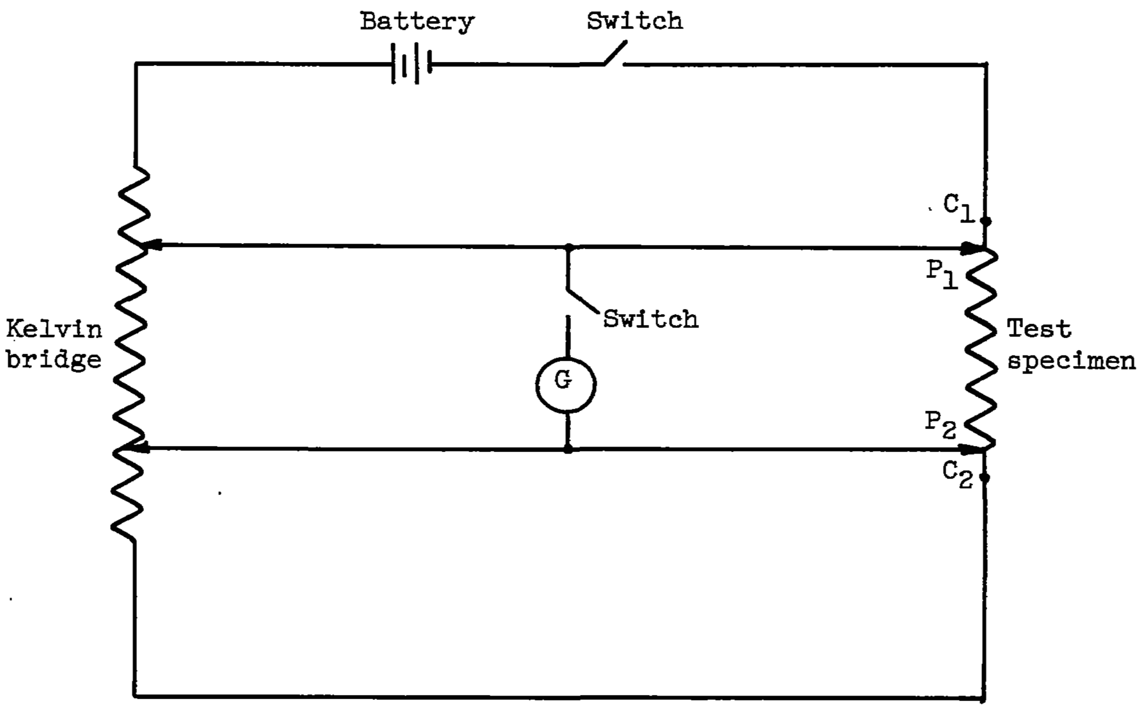


Figure 2. - Location of test specimens machined from blades. (All dimensions in inches.)



C_1, C_2	Current meter contacting points
G	Galvanometer
P_1, P_2	Potential contacts

Figure 3. - Schematic circuit diagram for measuring resistance of test specimens.

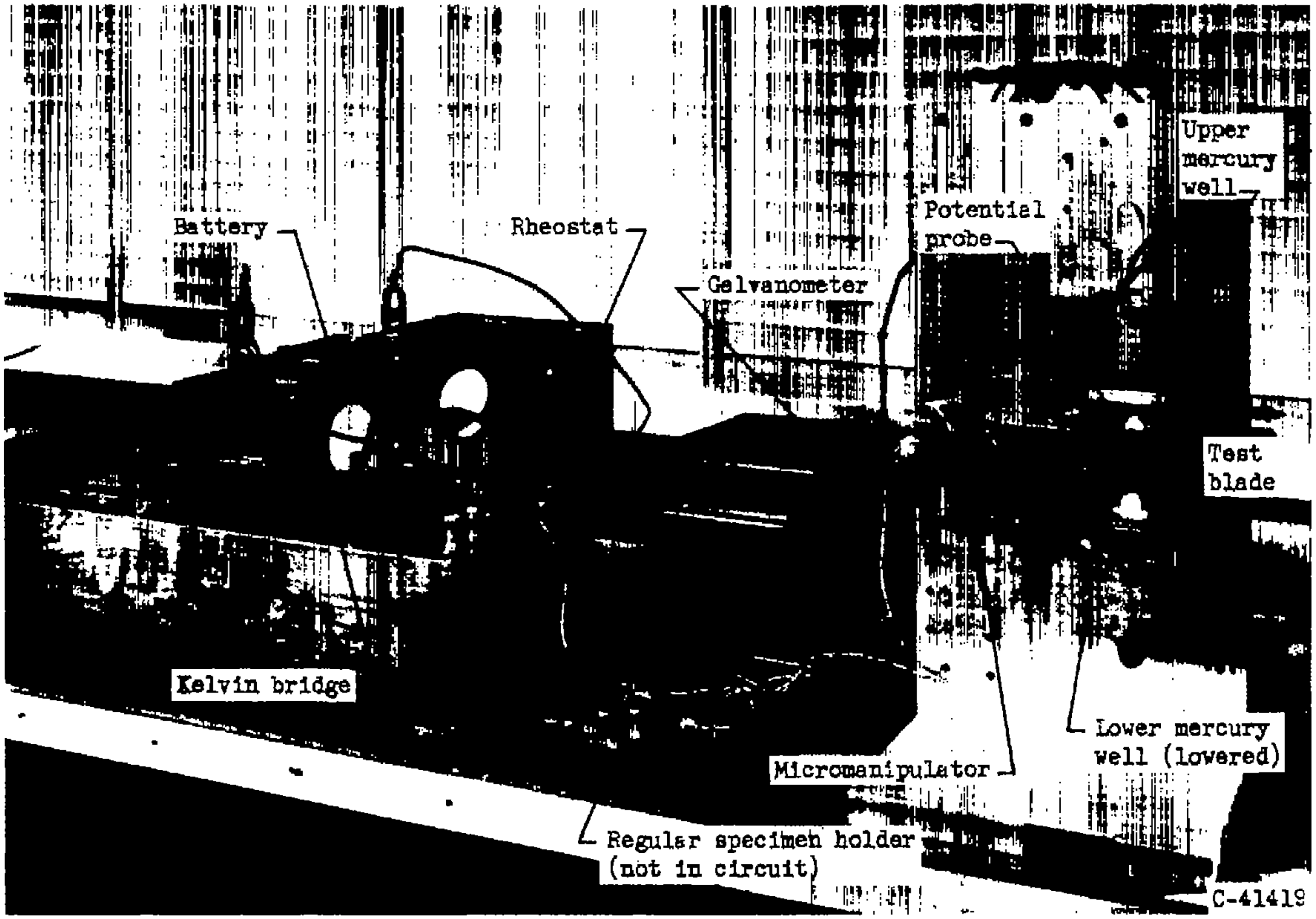
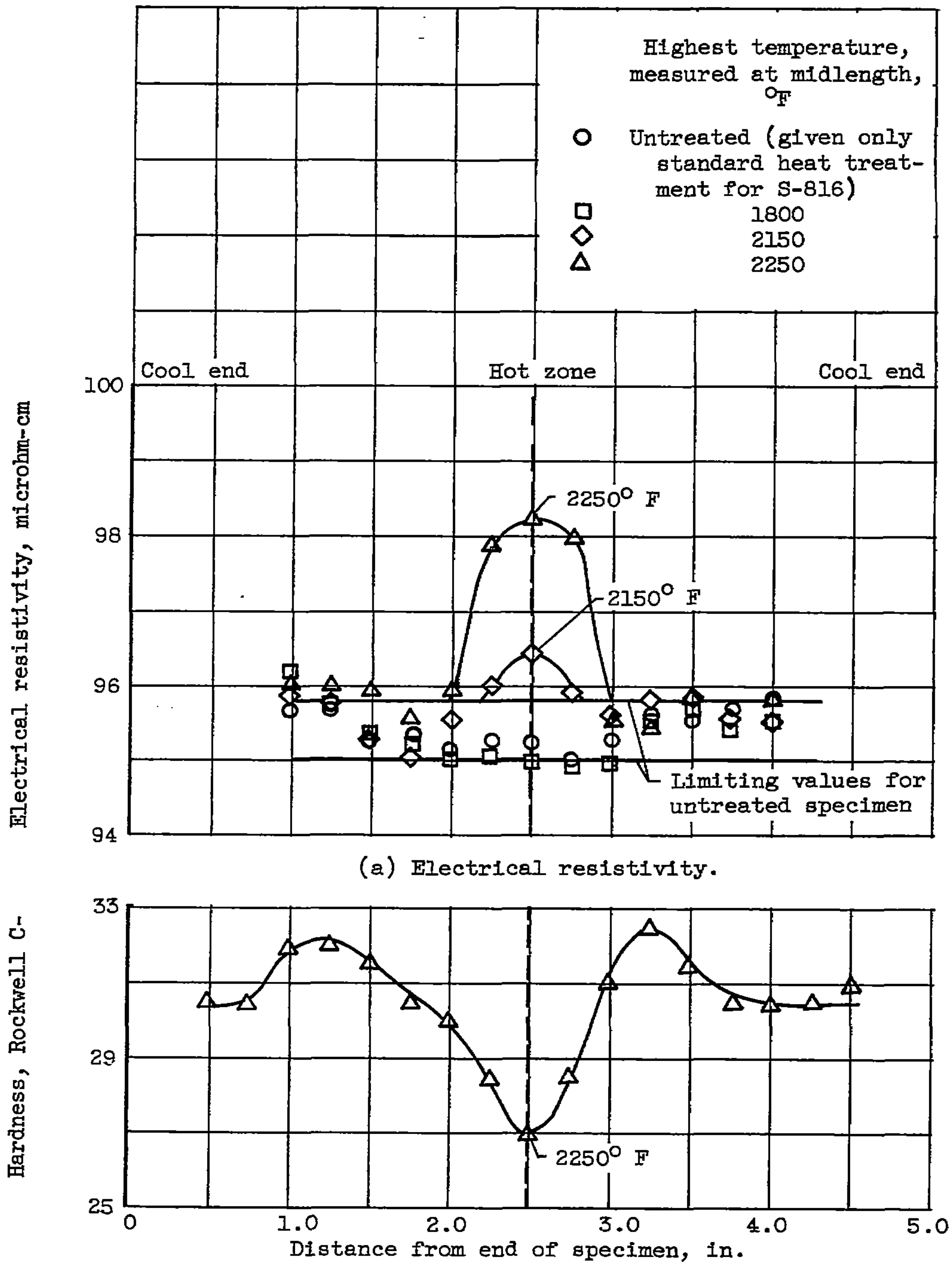


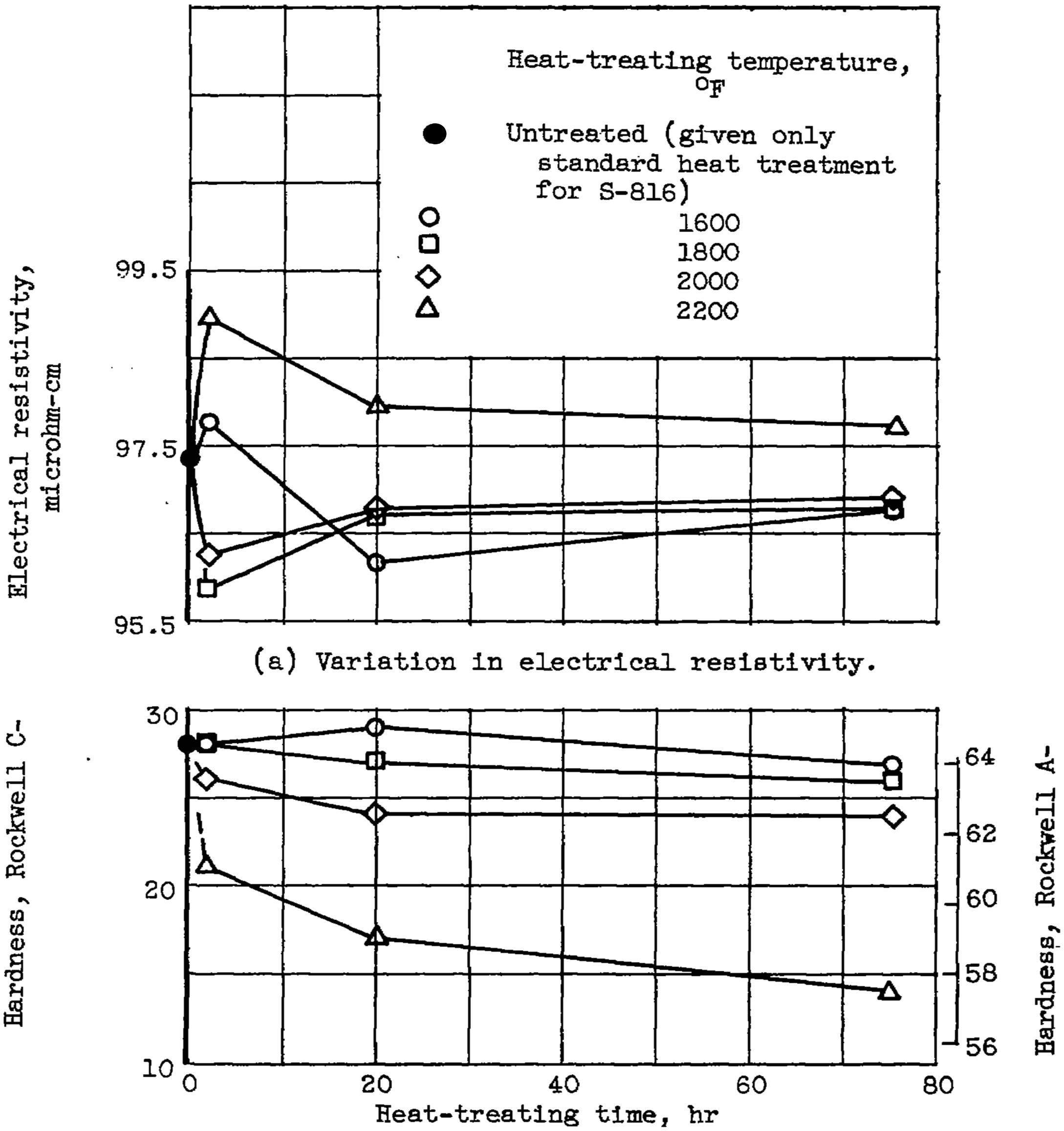
Figure 4. - Apparatus for measuring resistance of turbine blades and regular shaped specimens.



(a) Electrical resistivity.

(b) Hardness.

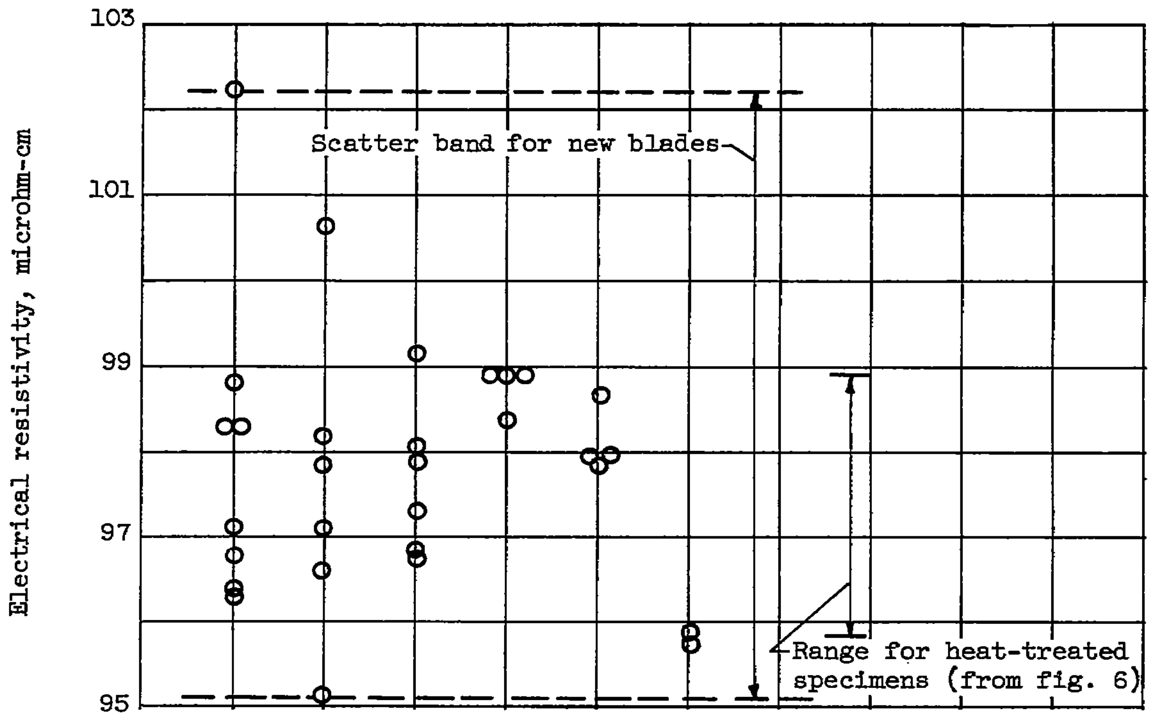
Figure 5. - Variation in resistivity and hardness along length of S-816 specimens heated for 15 minutes at their midlengths.



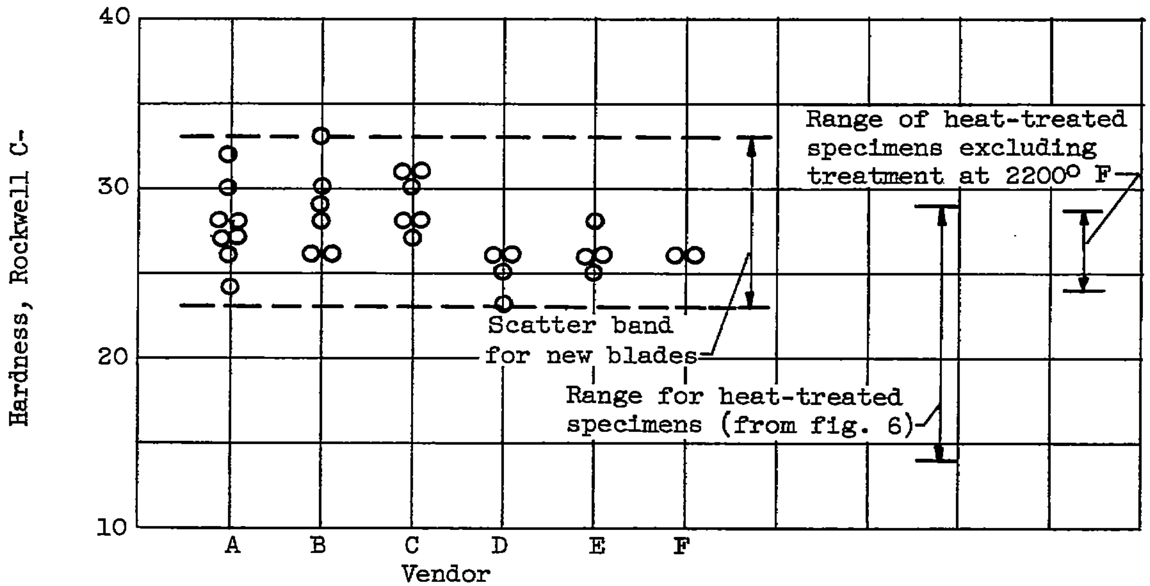
(a) Variation in electrical resistivity.

(b) Variation in hardness.

Figure 6. - Effect of heat treatment on properties of S-816.



(a) Electrical resistivity.



(b) Hardness.

Figure 7. - Scatter in resistivity and hardness of new S-816 turbine blades.

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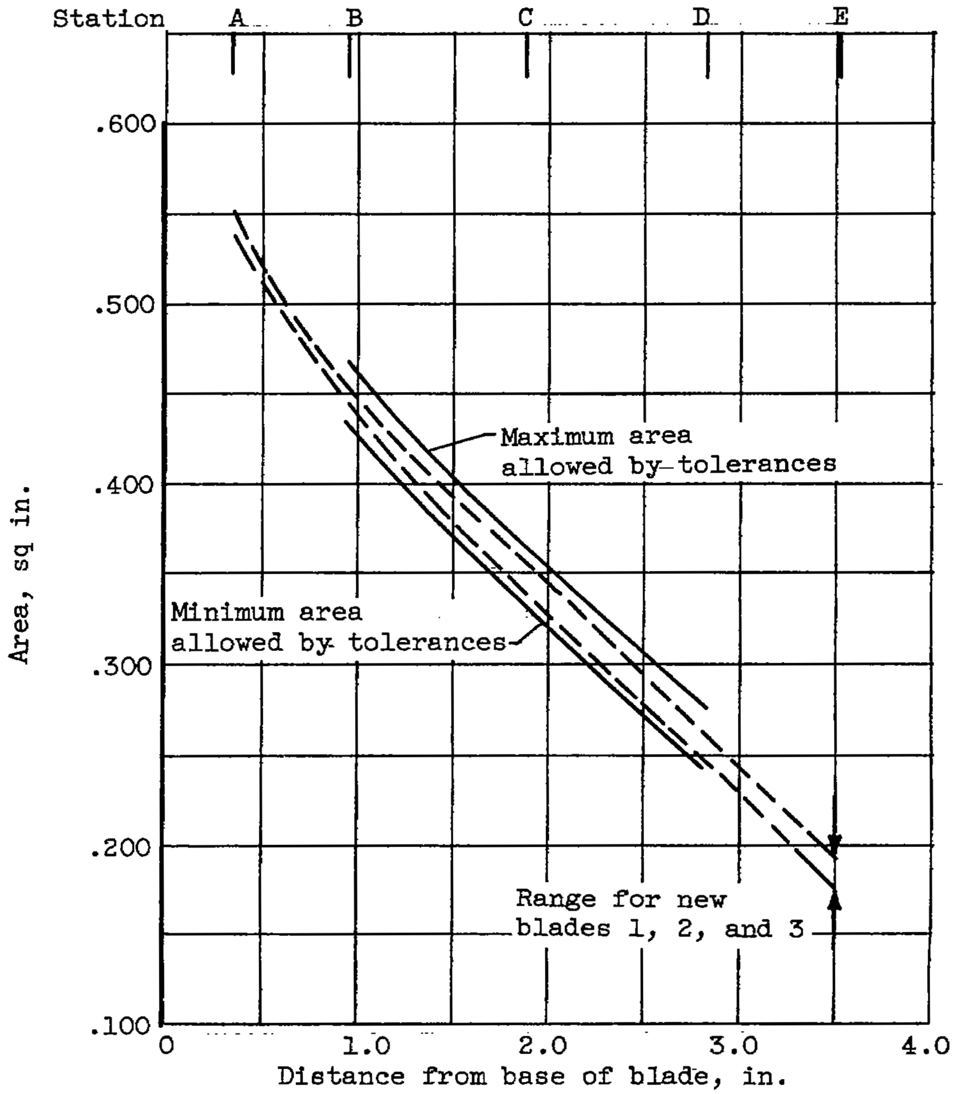

Figure 8. - Variation in cross-sectional area of S-816 turbine blades for one jet engine model.

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